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THESIS

DESIGN OF APPARATUS FOR THE DETERMINATION
OF AERODYNAMIC DRAG COEFFICIENTS
OF AUTOMOBILES

by

Brian R. Gritte

June 1984

Thesis Advisor: J. A. Miller

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There are three major components of the total resistance to motion of road vehicles: aerodynamic drag, rolling resistance in the form of tire friction on road surfaces and mechanical resistance in the form of bearing friction. Apparatus constructed at the Naval Postgraduate School, Monterey, California employs the measurement of total drag (aerodynamic drag + rolling resistance drag + mechanical drag) by means of coastdown

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testing and the measurement of rolling resistance and mechanical drag in an aerodynamic shielding trailer to determine the aerodynamic drag.

Data acquisition and reduction is carried out with a portable dedicated minicomputer system. The apparatus is designed to yield drag coefficients with an estimated uncertainty of about one percent.

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Design of Apparatus for the Determination of Aerodynamic Drag Coefficients of Automobiles

by

Brian R. Gritte
Lieutenant, United States Navy
B.S., University of Virginia, 1976

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 1984

ABSTRACT

There are three major components of the total resistance to motion of road vehicles: aerodynamic drag, rolling resistance in the form of tire friction on road surfaces and mechanical resistance in the form of bearing friction. Apparatus constructed at the Naval Postgraduate School, Monterey, California employs the measurement of total drag (aerodynamic drag + rolling resistance drag + mechanical drag) by means of coastdown testing and the measurement of rolling resistance and mechanical drag in an aerodynamic shielding trailer to determine the aerodynamic drag.

Data acquisition and reduction is carried out with a portable dedicated minicomputer system. The apparatus is designed to yield drag coefficients with an estimated uncertainty of about one percent.

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I. INTRODUCTION

Since the introduction of the automobile there has been an interest in improving the mileage obtained for a given amount of fuel consumed. Reduction of cost to the consumer motivated early engineering efforts and continues to do so. Since the oil crisis of the mid-seventies and the general interest in conservation of natural resources, reduction of fuel consumed is now an equally important factor.

There are three major components of the total resistance to motion of vehicles: aerodynamic drag, rolling resistance in the form of tire friction on road surfaces, and mechanical resistance in the form of bearing friction. An automobile travelling at today's speed limits expends about half of the energy developed by its engine overcoming aerodynamic drag. The purpose of the present work is to develop apparatus for the measurement of this aerodynamic drag.

II. AERODYNAMICS OF THE AUTOMOBILE

When an airfoil or other aerodynamic shape moves through an airmass it experiences aerodynamic forces created by both pressure and shear stresses acting on its surface. These aerodynamic forces are usually resolved into lift, the force perpendicular to the direction of motion, and drag, the force parallel to the direction of motion. The automobile experiences a lift force created by low pressure on the upper surface and high pressure on the lower surface. These pressure differences are created by the camber of the car and the fact that air must travel at a higher velocity over the top surface of the car to meet the slower moving air travelling in a straight line along the underside of the car. Through Bernoulli's equation one can see that if the air velocities are different, then the pressures created by these velocities must also be different:

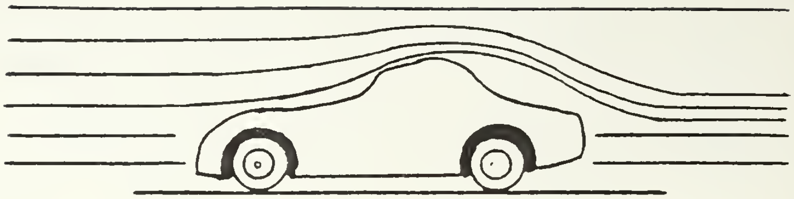
$$Ptop + \rho Vtop^2/2 = Pbottom + \rho Vbottom^2/2$$

Lift forces acting on a car may make the car hard to handle by reducing the force of the tires on the road. To create a negative or downward lift, a wedge-shaped front end can be employed. Also, downward projecting air dams which direct additional air up and over the car can be utilized to create a positive downward force. [Ref. 1]

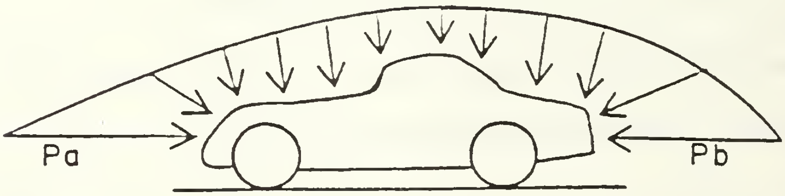
The component of the drag which results from shear stresses is called "skin friction"; the component which results from pressure forces is called "form drag". Skin friction drag is created as a result of boundary layer formation on the surface of a body as it moves through a viscous air mass. The velocity gradient in the boundary layer creates a shear stress tending to resist motion, given by Newton's equation:

$$T = F/A \alpha \mu dV/dY$$

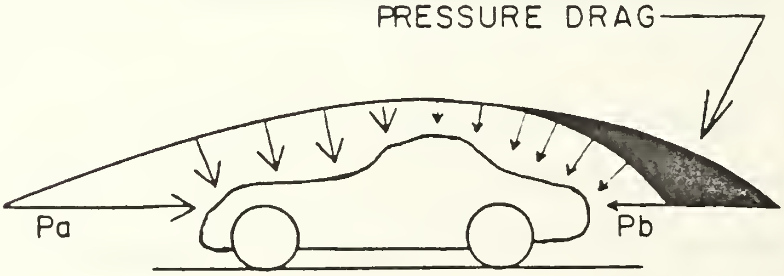
An automobile also experiences pressure drag which predominates over friction drag at lower velocities. Surface discontinuities in the form of mirrors, roof-racks, windshield-wiper blades, and sharp corners cause the otherwise smooth flow of air to separate from the surface of the vehicle creating pockets of turbulent air and increasing pressure drag which the energy supplied by the engine must overcome. Another contribution to pressure drag is the low pressure region behind the car. As the air flows over the car, separation occurs near the aft end forming a large wake which diminishes pressure recovery. At the point of separation, as shown in Figure 1, the pressure becomes constant and nearly equal to that at separation, and this



a. DISTURBANCE OF STREAMLINES AROUND VEHICLE



b. IDEAL PRESSURE PROFILE Pa = Pb



c. ACTUAL PRESSURE PROFILE Pa > Pb

Figure 1. Pressure Recovery Behind Vehicle

pressure is less than the pressure in front of the car. Thus, a net pressure force opposing forward motion is created. To combat this effect, many car manufacturers are using abrupt rear ends. The flow separates smoothly from the car forming a region of only moderately low pressure as opposed to a tapered rear end which produces a region of markedly lower pressure. [Ref. 2]

Frontal admission of engine cooling air also adds significantly to the drag. Air is slowed abruptly when passing through and cooling the radiator. Drag is further enhanced when the air enters the engine area rather than being directed around the outside of the car. Ventilating air which flows through the passenger area can create a pressure drag similar to the drag created by flow separation at the rear of the car. Air enters the front at a high pressure and vents to the rear at a lower pressure. This pressure differential creates a force which opposes the direction of motion.

Drag characteristics of a vehicle may be characterized by the dimensionless drag coefficient Cd, defined by the equation: $D = CDqA$. Rearranging the equation yields Cd as a function of drag force, dynamic pressure, and frontal area: $Cd = D/qA = D/(1/2\rho V^2 A)$. D is the total drag force, A is the characteristic frontal area, and q is the dynamic pressure, $(1/2\ \rho V^2)$, where ρ is the air density and V the vehicle velocity. An important conclusion is that vehicular drag varies as the square of the velocity and directly as the frontal area and drag coefficient.

As drag coefficients are difficult to compute theoretically for even simple aerodynamic shapes, the only practical means for determining them for complex shapes such as an automobile is experimentally. Automobile manufacturers currently publish values of drag coefficients for their vehicles as verification of their claims of aerodynamic efficiency. However, no standards currently exist in the industry by which the consumer can compare the drag coefficient of one manufacturer against another. [Ref. 3]

III. EXPERIMENTAL MEASUREMENT OF DRAG

The experimental measurement of drag involves the measurement and isolation of the aerodynamic forces on a vehicle. The solution adopted herein employs the measurement of total drag (aerodynamic drag + rolling resistance drag + mechanical drag) by means of coastdown testing and the measurement of rolling resistance drag and mechanical drag in an aerodynamic shielding trailer. The rolling resistance and mechanical drag measured in the trailer can then be subtracted from the total drag obtained from coastdown testing with the resultant being the aerodynamic drag. The concepts of coastdown testing and rolling resistance testing are not new. The use of coastdown testing for aerodynamic drag has been studied be several authors since 1927. [Ref. 4] The Motor Industry Research Association of Warwickshire, England has shown a shrouded rolling resistance trailer to be a practical means of isolating a car from aerodynamic forces. The coastdown test apparatus and rolling resistance trailer used in this work were designed and constructed at the Naval Postgraduate School, Monterey, California.

IV. COASTDOWN TESTING

A. APPARATUS

Coastdown testing has been shown to be a viable means of measuring the total forces acting on a vehicle on the open road, consisting of aerodynamic drag, rolling friction drag, and mechanical drag. A fifth wheel apparatus (Figure 2) is used to measure velocity and an accelerometer mounted on the vehicle is used to measure acceleration. Knowing the weight of the car (tare + fuel + cargo) and the acceleration and using Newton's Second Law, $F = ma$, the total drag experienced by the vehicle can be computed. A Hewlett-Packard 3421A Data Acquisition/Control Unit (Figure 3) and an HP-41CV Programmable Calculator (Figure 4) were used for the data acquisition and reduction.

The fifth wheel apparatus consists of a 20-inch BMX bicycle wheel and fork mounted on a shop fabricated aluminum frame. A spring-loaded and damped strut is used to hold the tire on the road and to act as a shock absorber. This frame and wheel assembly is bolted to a commercially obtained suction disk which is used to attach the entire assembly to the side of the test vehicle. This seemingly unsecure mount has withstood testing on a Porsche travelling at 180 mph! [Ref. 5] On vehicles not having a suitable surface for suction disk mounting, the suction disk can be

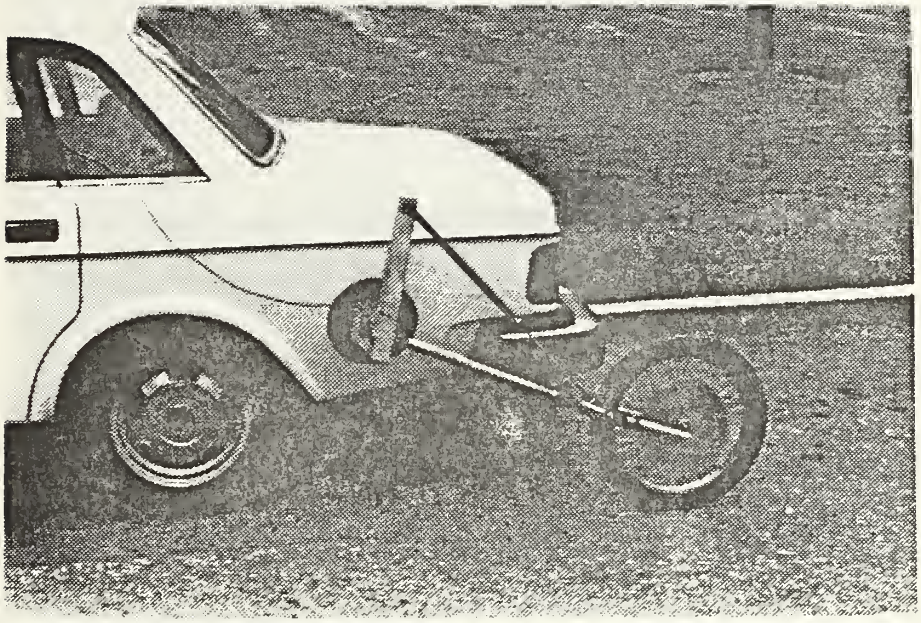


Figure 2. Fifth Wheel Apparatus Attached to Car

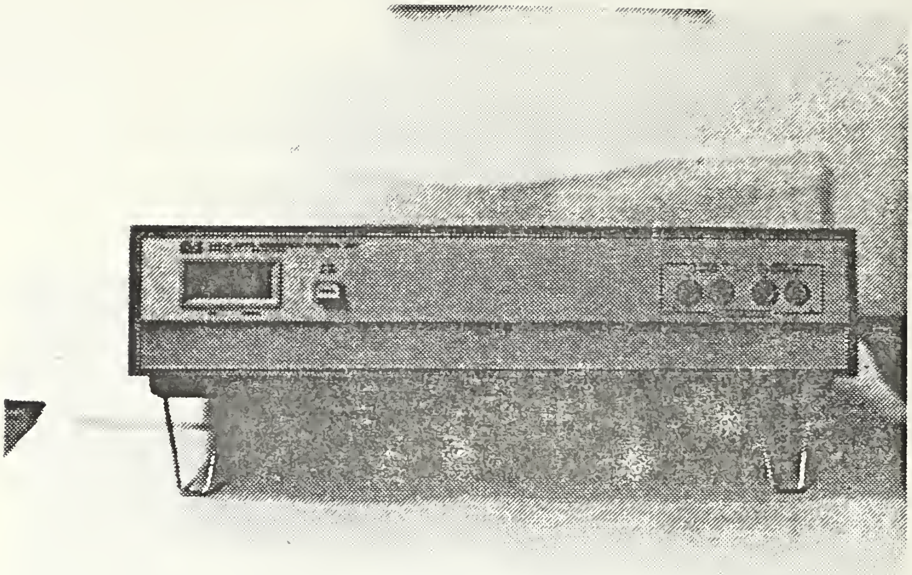


Figure 3. HP-3421A Data Acquisition/Control Unit

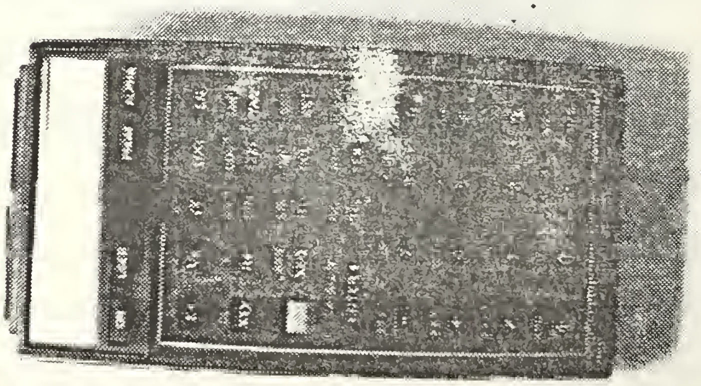


Figure 4. HP-41CV Alphanumeric Programmable Calculator

removed and the entire apparatus attached to a rear bumper using bungee cords. The HP-3421A Data Acquisition Unit receives its speed information from impulses produced by an optical switch triggered by a toothed stainless steel ring that is mounted concentric with the axis of the fifth wheel. (Figure 5) The acquisition unit measures frequencies to 10 KHz with a resolution of 1Hz by counting the number of impulses per second being generated by the optical switch. Frequency is converted into velocity in miles per hour or feet per second with the HP-41CV calculator which is integrated into the data acquisition system.

A Statham A3TC±1-350 accelerometer (Figure 6) fastened to a universal tripod head with leveling bubbles and a suction disk for convenience of window mounting is used to obtain acceleration data. The accelerometer is powered by a portable 12-volt source in conjunction with a plug-in connection to the cigarette lighter to make use of the automobile battery. The accelerometer is calibrated so one G of acceleration or deceleration produces a one volt output. The HP-41CV, then, receives its acceleration information in terms of G's produced.

The heart of the data acquisition and reduction system is the Hewlett-Packard Interface Loop (Figure 7) consisting of:

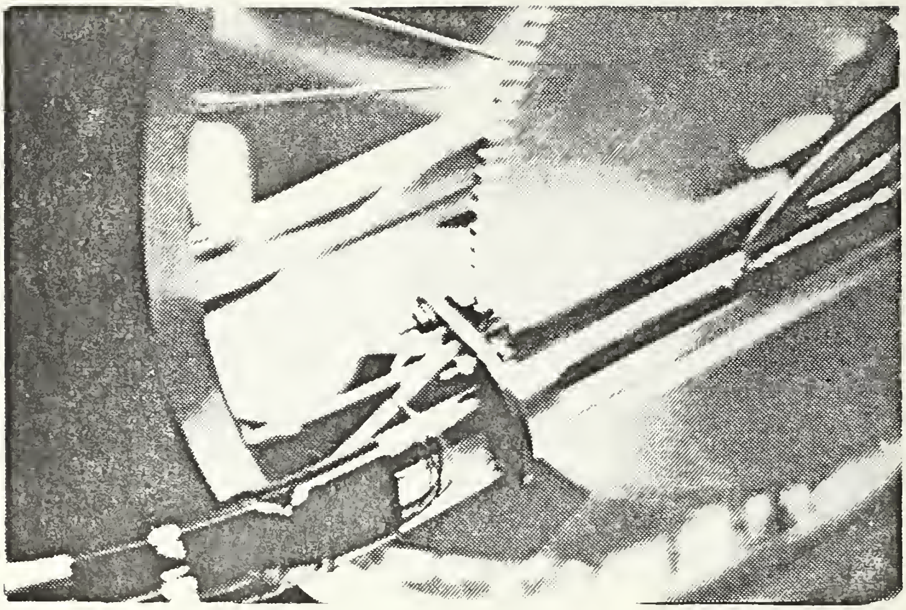


Figure 5. Optical Switch

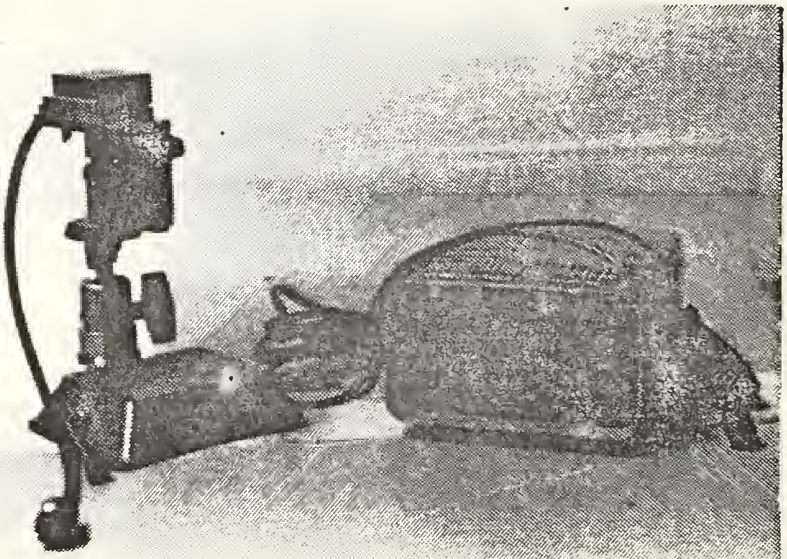


Figure 6. Accelerometer and Interface Unit

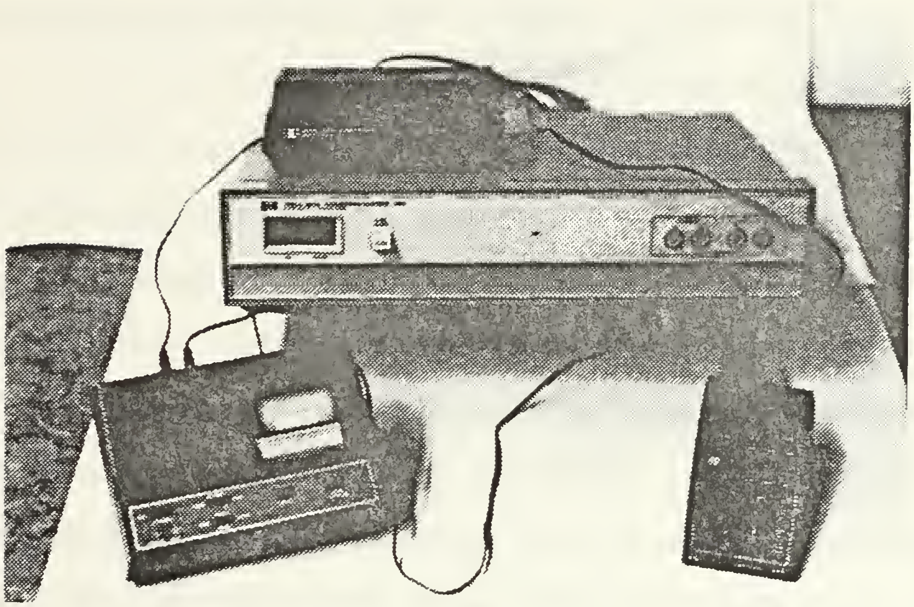


Figure 7. Data Acquisition and Reduction System

1. HP-3421A Data Acquisition/Control Unit
2. HP-82160A HP-IL Module
3. HP-82162A Thermal Printer
4. HP-82161A Digital Cassette Drive
5. HP-41CV Alphanumeric Programmable Calculator containing:
    a. HP-44468A Data Acquisition/Control ROM PAC
    b. HP-82182A Time Module
    c. HP-41C Math PAC

With the instrumentation mounted on a vehicle, the acquisition unit can receive inputs of frequency from the optical switch and voltage from the accelerometer. Coastdown testing is accomplished by allowing a vehicle to decelerate, out of gear, on a straight, level road from an initial speed of 65-70 miles per hour. A program within calculator memory is activated which automatically acquires simultaneous speed and deceleration data. Data is taken at each 5 or 10 miles per hour speed decrement, optionally, from an initial speed taken at 60 miles per hour to a zero speed indication. These readings are stored in calculator memory and printed simultaneously on a line printer. When the test is complete a printout of total drag and velocity in miles per hour is generated for each speed. A curve-fitting algorithm from the HP-41CV Math PAC is then used to produce a power series expression for the curve of drag versus speed.

B. COASTDOWN TEST SOFTWARE

Software for the coastdown apparatus, as well as the entire test procedure, is written in HP-41CV programming language and can be stored on magnetic cards or in calculator memory. The program and the data which it collects and generates can be stored within the calculator without the use of peripheral storage devices. The reader is referred to the Hewlett-Packard texts in the Bibliography for information concerning HP-41CV operation. The calculator should be sized to 70 to allow the proper allocation of registers for data storage. It is also recommended that all other programs be purged from calculator memory prior to loading the four software programs contained in the entire test procedure. Figure 8 is a flow diagram for the coastdown test sequence; a listing of the actual program steps with complete program description, sample data output, and list of storage registers used can be found in the Appendix.

C. INSTALLATION OF INSTRUMENTATION

Note: A basic working knowledge of the HP-41CV calculator is assumed; the reader is directed to the Bibliography for detailed information concerning the basic operation.

Referring to Figure 9, the equipment necessary to obtain and record coastdown data are the fifth wheel, the data acquisition unit, the HP-41CV calculator, thermal printer, power pack, accelerometer, and accelerometer/tow

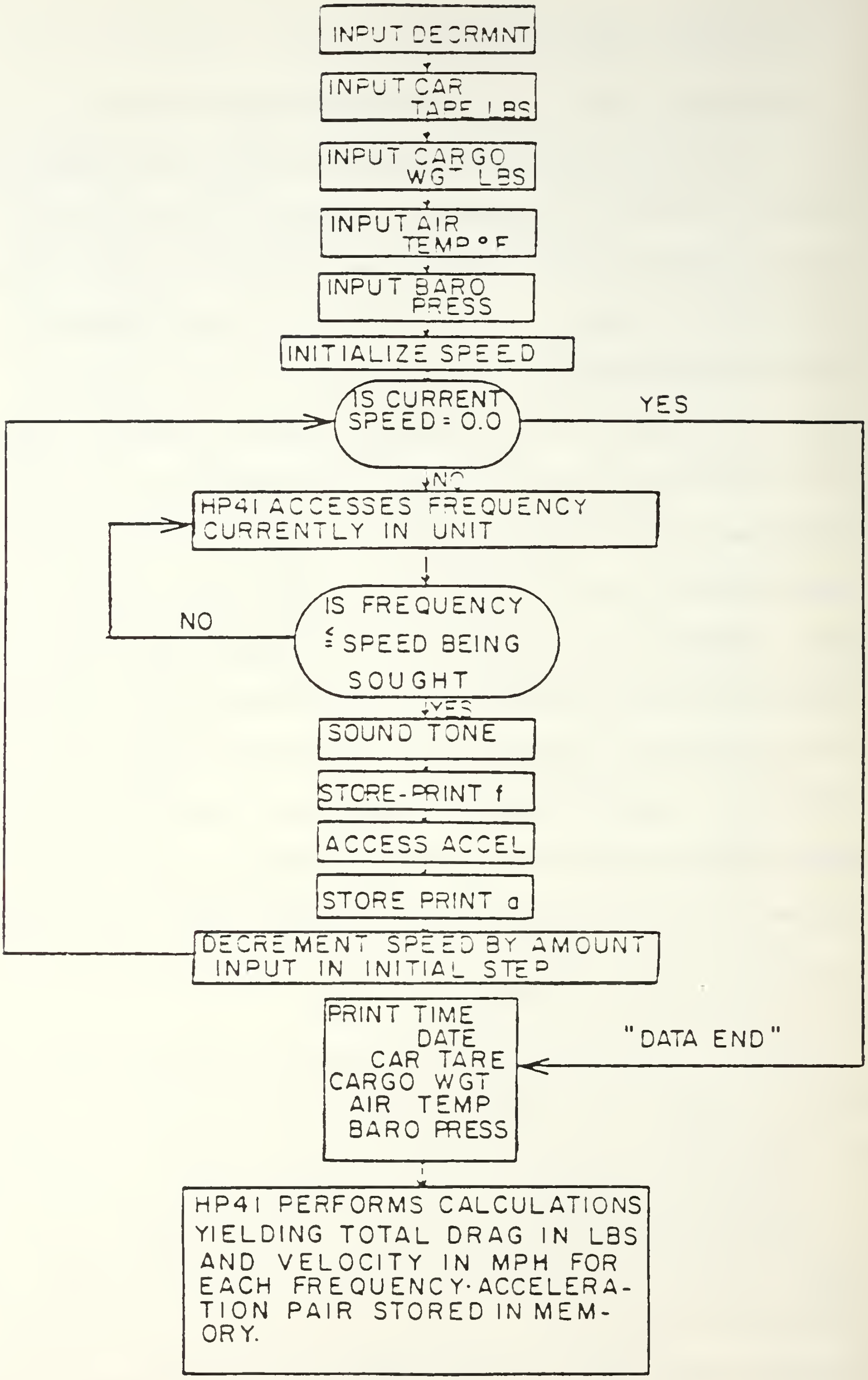

INPUT DECRMNT
INPUT CAR TARE LBS
INPUT CARGO WGT LBS
INPUT AIR TEMP °F
INPUT BARO PRESS
INITIALIZE SPEED
IS CURRENT SPEED = 0.0
YES
NO
HP41 ACCESSES FREQUENCY CURRENTLY IN UNIT
IS FREQUENCY ≤ SPEED BEING SOUGHT
NO
YES
SOUND TONE
STORE-PRINT f
ACCESS ACCEL
STORE PRINT a
DECREMENT SPEED BY AMOUNT INPUT IN INITIAL STEP
PRINT TIME DATE CAR TARE CARGO WGT AIR TEMP BARO PRESS
"DATA END"
HP41 PERFORMS CALCULATIONS YIELDING TOTAL DRAG IN LBS AND VELOCITY IN MPH FOR EACH FREQUENCY·ACCELERATION PAIR STORED IN MEMORY.

Figure 8. Coastdown Test Flow Diagram (CDT)

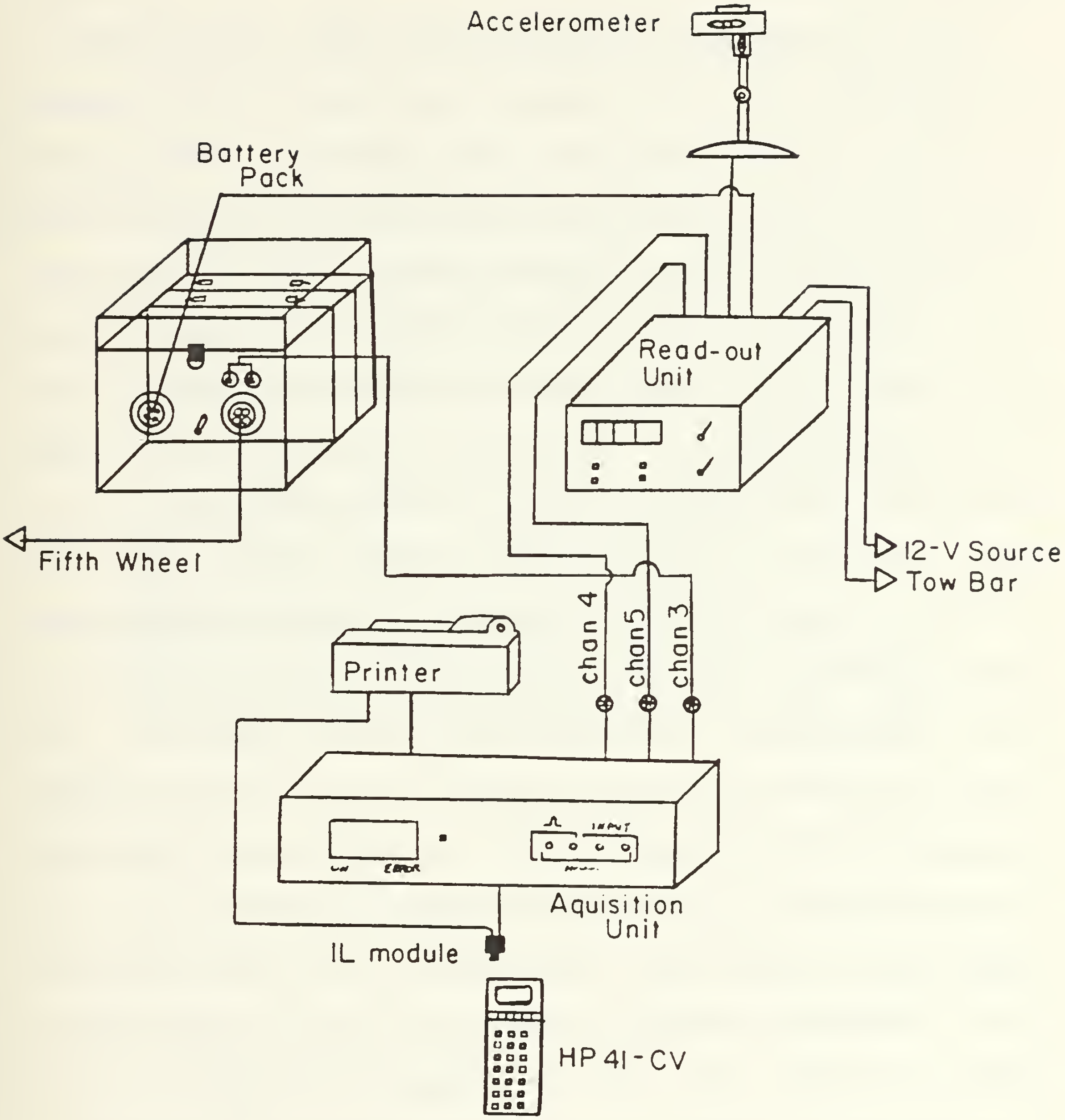


Figure 9. Apparatus Wiring Diagram

bar interface unit. These pieces, along with a towing force transducer are also the equipment necessary to obtain and record data from the shrouded trailer test procedure, to be discussed below.

Set-up begins with HP-IL interface loop. This consists of the HP-41CV, the data acquisition unit, the HP-IL module with wires attached, and the thermal printer. (See Figure 7) Be sure that the calculator and peripheral devices are turned off before connecting or disconnecting the HP-IL module and cable connectors. If this is not done the calculator may be damaged and/or the system may not interface properly. The HP-IL module plugs into any of the calculators ports. One must push in the module, with switch face DOWN, until it snaps into place. The peripheral devices in the interface loop may be connected in any order as long as a continuous loop is formed. The connectors are designed to ensure proper orientation. The final loop consists of HP-IL module to printer, printer to acquisition unit, and acquisition unit to HP-IL module. Note that the printer function switch on the HP-IL module must be set to DISABLE. A communication circuit has now been formed in which data or instructions are transferred from one device to the next around the loop. This forms the "heart" of the data acquisition and processing system. The three black connectors on the rear panel of the acquisition unit are connected to the external transducers used to generate the three forms of input necessary. They are connected to channels 3, 4, and 5 of the acquisition unit and are so labelled.

The battery pack (Figure 10) is a Plexiglas case containing 12-volt battery and two small 1.5 volt batteries. The large battery is used for the accelerometer/tow bar bridge supply and the 1.5 volt batteries power the optical switch on the fifth wheel. On the front of the Plexiglas case are two large male and female connectors separated by a small toggle switch. Above the female connector are two small jacks, one red and one black. The male plug on the left is to be attached to the grey cable from the accelerometer readout unit labelled 12-V SOURCE. The female receptable on the right is to be attached to the grey cable from the optical switch on the fifth wheel. The two small receptacles are to be connected to the channel 3 transducer cable from the rear of the acquisition unit. This connector provides the acquisition unit with frequency data from the optical switch when the toggle switch is in the UP (ON) position. (Leave the toggle switch in the down position when not in use to prevent the two 1.5 volt batteries from discharging.)

The cable labelled CHAN 5 OUPUT at the rear of the interface unit connects to the channel 5 wire on the rear of the acquisition unit. At the end of the cable is a

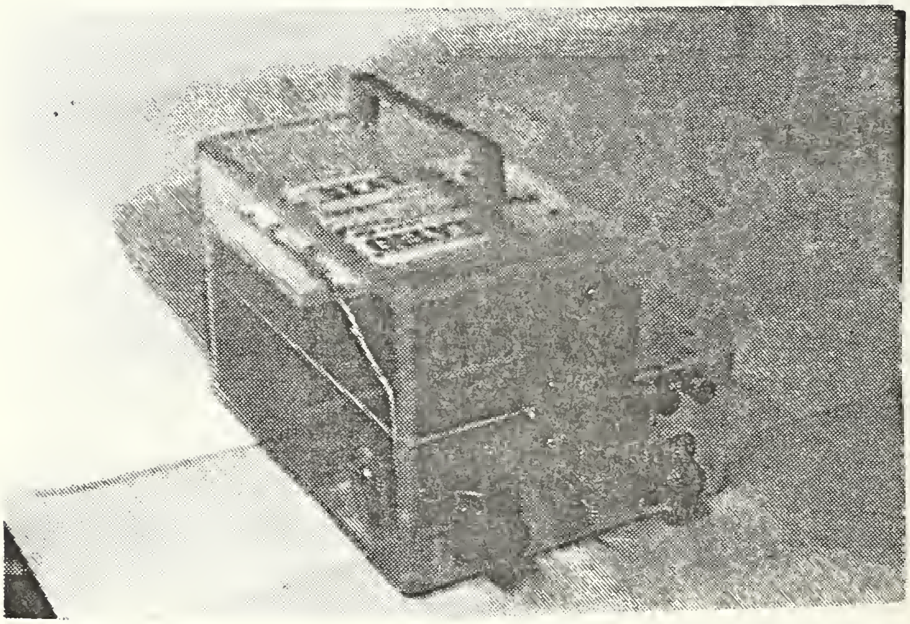


Figure 10. Battery Pack

black and red connector; be sure that the black connector matches with the ground side of the connector on the wire coming from the back of the acquisition unit. The grey cable from the accelerometer unit, labelled ACCELEROMETER INPUT, attaches to the accelerometer; the cable from the accelerometer unit, labelled 12-V SOURCE, plugs into the cigarette lighter of the vehicle to be tested. This completes the apparatus hookup; channel 4 wire on the rear of the acquisition unit and the leads labelled TOW BAR INPUT and CHAN 4 OUTPUT on the interface unit are not used during the coastdown procedure. (See Figure 11.) Arrangement within the vehicle is arbitrary; however, an arrangement similar to that shown in Figure 12 has been found to be successful.

D. TEST PROCEDURE

Coastdown testing with the fifth wheel is carried out on a long, straight, level segment of road several miles in length. An accurate tare weight of the test vehicle is necessary. This weight should include all standard items; one should ensure that the amount of fuel in the tank during road test is generally the same as during tare weigh-in. The total weight of personnel, cargo, and test equipment to be carried in the vehicle during test must also be known accurately. Prior to the coastdown test, the following information should be recorded:

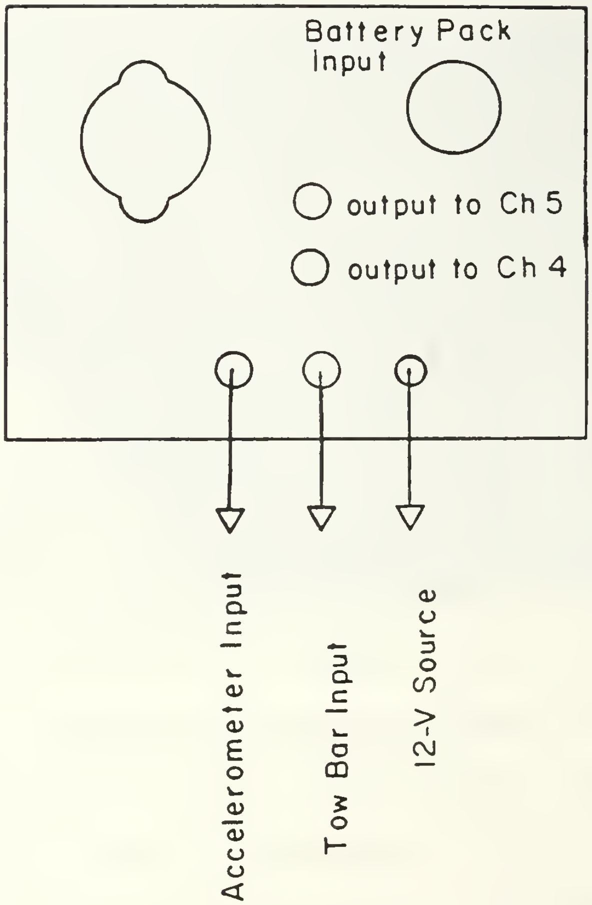


Figure 11. Rear of Accelerometer/Tow Bar Interface Unit

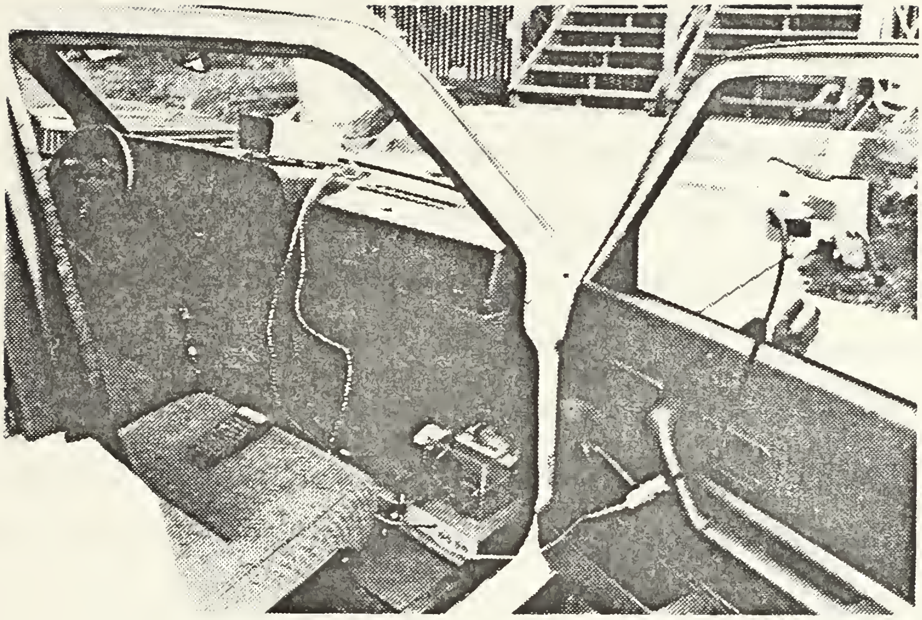


Figure 12. Typical System Arrangement

1) Vehicle

    a. Year, make, model.

    b. Presence of any external protuberances, i.e., mirrors, racks, etc.

    c. Tires-type (radial, poly, etc., tire pressure, estimation of condition.

    d. Odometer reading.

    e. Transmission type.

2) Weather

    Temperature, barometric pressure, wind speed. Testing should be carried out only during light and steady wind conditions.

3) Road

    a. Type - asphalt, cement, etc.

    b. An estimation of condition, i.e., smooth surface, rough surface, wet, dry, etc.

    c. A statement of straightness and level.

In addition to the above written documentation, photographs of tire and road conditions may be helpful in establishing a data base from which to reference future testing.

Installation of the wheel on the vehicle should be accomplished immediately prior to testing. It is not recommended that the fifth wheel be attached during travel to and from the test site. The recommended test team consists of a minimum of two individuals - a driver and an equipment operator. Although it is possible that, once thoroughly familiar with the equipment, a single individual can drive and operate the equipment simultaneously, it is not recommended because of safety considerations.

To attach the suction disk to the side of the vehicle, place it on the surface with the least curvature on the left rear of the body. (See Figure 2.) Ensure that the disk lies flat and that the edges of the disk form an effective seal with the vehicle body. Tension placed on the wheel by the shock-strut can be adjusted by rotating the disk clockwise while holding the wheel in place. This is most easily accomplished by two people. Once the desired tension is obtained, begin pumping the gold plunger on the suction disk being sure to hold the disk flush with the car body. When the red ring painted around the plunger disappears from view, a proper vacuum has been created and the disk is securely fastened to the body. On vehicles with no available space for the suction disk mount, the strut and/or disk can be removed and the fifth wheel mounted on the rear bumper of the car with bungee cords. The grey cable from the optical switch can be threaded through the left rear window of the vehicle and connected to the battery box as described above.

The accelerometer is also a suction mounted device. It can be mounted anywhere in the vehicle where a flat, nonporous surface can be found, such as a window.

(See Figure 12.) The universal fixture which connects the accelerometer to the suction base allows great flexibility in mounting the accelerometer; the bubble levels are provided for leveling and their use is described below.

To initialize the system, first ensure that the cigarette lighter connection is secure. Place the toggle switch (ON/OFF CHARGE) on the front panel of the accelerometer interface unit in the ON(UP) position. Numbers should appear on the LED meter. This activates the optical switch. At this point it is recommended that the channel 3 and 5 wires on the acquisition unit be disconnected until system initialization is completed. With the calculator turned OFF and the thermal printer turned ON, press the power switch on the front of the acquisition unit into the ON position. The HP-3421A now performs a series of eight internal tests; if any of them fails, an error indicator in the form of a T will appear in the lower right corner of the liquid crystal display above the word error. Next, there will be an audible "click" from inside of the acquisition unit and all of the numbers on the liquid crystal display will light up for about one second. A failure detected by any of these self-tests will be indicated by one or more numbers re-lighting in the display indicating which test(s) failed. After the self-test, the "click" will be heard again; if no error indication is seen in the lower right corner of the liquid crystal panel, then all systems are functioning properly. (The reader is directed to the HP-3421A data acquisition/control unit operating, programming, and configuration manual for error indications.) The channels 3 and 5 wires on the rear of the acquisition unit should now be reconnected.

A NOTE ON REMOTE OPERATION: Both the thermal printer and acquisition unit should be connected to an AC power source when not in use. When both are fully charged, the acquisition unit should provide a minimum operating time of 12 hours and the printer should sustain portable printing for 4000 to 5000 lines. The portable battery pack can be charged by connectin the cigarette lighter plug to a 12 volt source, connecting the large 5 pin connector from the rear of the accelerometer read-out unit to the battery pack, and placing the toggle (ON/OFF CHARGE) on the front of the interface unit in the DOWN(OFF-CHARGE) position. If all the units are kept properly charged, trouble free operation will be the result.

Mount the accelerometer on the passenger side window by pressing the rubber suction mount flush against the glass and rotating the lever on the mount to create a vacuum. Once the accelerometer is firmly mounted, the apparatus must be manipulated on its universal fittings until the bubble level mounted parallel to the accelerometer unit indicates level. At this time the little arrow on the accelerometer unit should point DOWN.

Calibration of the accelerometer is accomplished using the accelerometer interface unit, the HP-41CV calculator, and the data acquisition/control ROM PAC. The ACCEL/TOW toggle switch should be in the ACCEL(UP) position. With the little arrow on the accelerometer unit pointing DOWN and the bubble reading level, the accelerometer will be calibrated to read 1.0 G. At this time execute the ROM Front Panel routine on the HP-41CV by executing "FP". The HP-41CV display will show "initialize--" followed by "**HP3421A**" and then "--------". The system is now initialized and the calculator is in user mode. Press the letter "A" button on the calculator and the HP-41CV will respond with "DCV" followed by "CHANNEL?".

NOTE: The FP routine will periodically pause momentarily. This is because the HP-41CV can only acknowledge key closures while it is paused. Consequently, if you press a function key while the FP routine is running, there is a very slight chance that the HP-41CV might not catch it. If this occurs simply press the function key again and hold it down until the HP-41CV responds. [Ref. 6]

Calibration of the accelerometer interface unit on channel 5 is desired, so respond with "5" and then press "R/S". Channel 5 will close in the acquisition unit and accelerometer voltage readings will be continuously displayed on the HP-41CV. With a small jeweler's screwdriver, turn the accelerometer "full-scale adjust" potentiometer on the face of the accelerometer interface unit until 1.000 to three significant digits after the decimal point is seen on the calculator.

The LED display on the accelerometer interface unit will read similarly but do not use this for calibration as the HP-41CV is more accurate. The LED meter will be used only for reference during the test procedures. Now, rotate the accelerometer unit until the bubble perpendicular to it is level and the little arrow is pointing in a fore and aft direction. With the jeweler's screwdriver, turn the accelerometer "zero adjust" potentiometer on the face of the accelerometer interface unit until 0.000 is read on the HP-41CV. Check both of these adjustments once more; the accelerometer unit is now calibrated and ready for use. Leave the accelerometer in the horizontal position; any fore and aft acceleration or deceleration of the vehicle during the test will be read as a plus or minus voltage reading on the interface unit and recorded, as appropriate, on the printout. Press the "R/S" button on the HP-41CV to halt the procedure and then clear the calculator display of any remaining readouts.

Now, the instrumentation is ready for coastdown testing. Activate the coastdown program within the HP-41CV by executing "CDT". The HP-41CV will prompt with "5 or 10 miles per hour inc?" An entry of 5 will mandate that data points be taken every 5 miles per hour descending from 60 miles per hour and an entry of 10 will set 10 miles per hour increments. After each prompt and entry, press the "R/S" button. Input car tare in pounds, cargo weight in pounts, air temperature in degrees fahrenheit, and barometric pressure in inches of mercury. DO NOT PRESS "R/S" AFTER THE BAROMETRIC INPUT. The program is now initialized and depression of the "R/S" will activate the speed search. Accelerate the vehicle up to a speed greater than 60 miles per hour, depress the "R/S" button on the calculator, place the car in neutral and allow it to coast to a slow speed (less than 5 miles per hour) or to a stop. The first printout should be seen within 5-7 seconds after the vehicle's speed descends through 60 miles per hour. An occasional glance at the accelerometer interface unit should verify that a deceleration is being sensed. The calculator will access and print a frequency and voltage every 5 or 10 miles per hour decrement down to zero. The calculator will then perform computations and printout a list of measured velocities in miles per hour and drag in pounds for each data point taken during the coastdown.

Next, using total drag as the Y values and velocity in miles per hour as the X values, enter, the "POW" subroutine of the HP-41CV "LIN" program and calculate the constants "a" and "b" which the "POW" program computes. These constants correspond to a curve of velocity versus drag in the form of $Y = "a" X^{"b"}$. Record the constants, as they will be needed in the final data reduction program to determine aerodynamic drag coefficients.

V. ROLLING RESISTANCE TESTING

A. APPARATUS

The second part of the aerodynamic testing, as described above, is the measurement of rolling resistance drag and mechanical drag in a shrouded rolling resistance trailer. (See Figure 13.) The purpose of the shrouded trailer is the isolation of the vehicle from aerodynamic forces. The vehicle is towed by means of a tow bar inside the trailer and the trailer is, in turn, towed behind another vehicle. Rubber skirting which encircles the entire trailer seals the vehicle inside from any air flow. The tow bar within the trailer is instrumented with calibrated strain gauges in order to measure towing force directly. (See Figure 14.) This force is due only to rolling and mechanical friction since aerodynamic forces have been eliminated. The instrumentation used to measure and record this force is the same as that used for the coastdown testing, with two changes: appropriate operational software has been provided and channel 4 of the data acquisition unit is used to acquire the voltage representing the towing force from the strain gauges mounted on the interior towing apparatus. As in coastdown testing, the fifth wheel is used to measure the speed and the accelerometer is mounted in the towed vehicle to measure any acceleration/deceleration

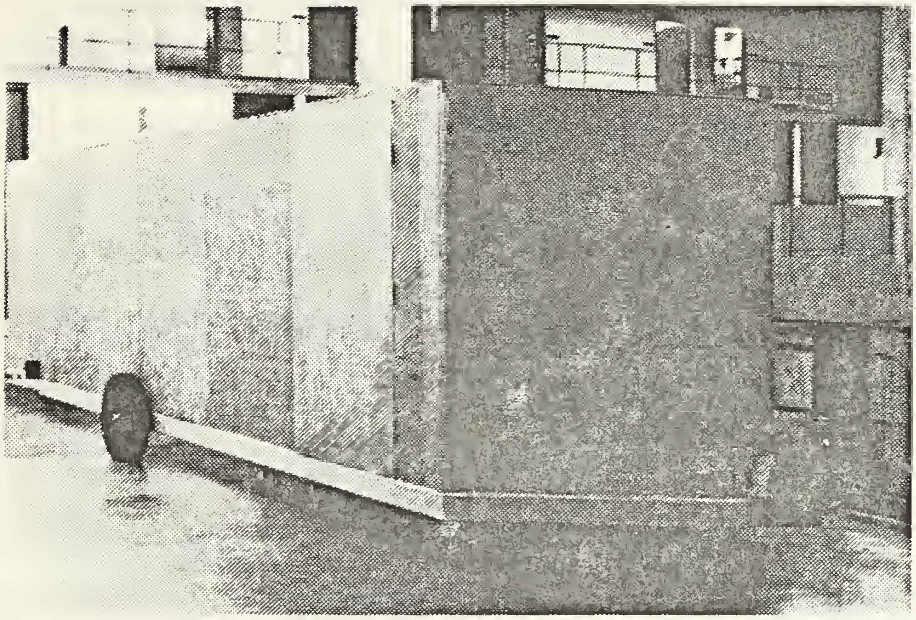


Figure 13. Rolling Resistance Trailer

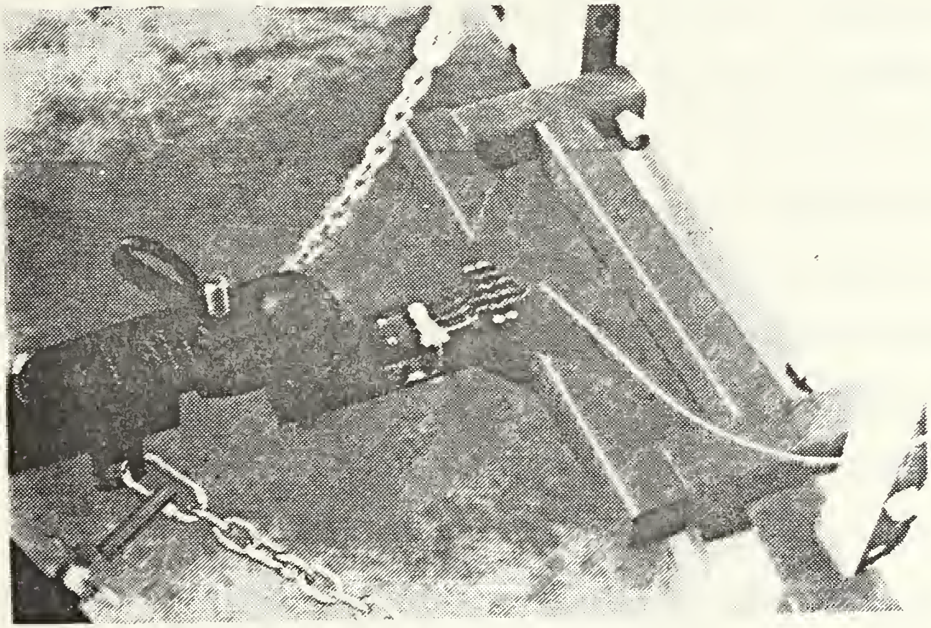


Figure 14. Instrumented Tow Apparatus

which may occur. With the empty weight of the vehicle and weight of cargo known, the rolling drag can be calculated using Newton's Second Law, by multiplying the mass by the acceleration and adding to it the force experienced by the two bar:

$$D_{\text{Rolling Friction}} = (w/g)a + D_{\text{Towing Force}}$$

In the process of making measurements, the trailer and vehicle are towed in a straight line at varying speeds and the Hewlett-Packard acquisition system acquires and records the necessary data: speed in terms of frequency, acceleration in terms of voltage, and towing force in terms of voltage. When the acquisition unit detects a speed of zero it halts data acquisition and begins data reduction. In a manner similar to the coastdown test printout, the data processing system prints out a value of rolling drag and velocity in miles per hour for each data point acquired. One then enters the "POW" subroutine of the HP "LIN" program using rolling drag as the "Y" values and velocity in miles per hour as the "X" values and obtains the constants "$\bar{a}$" and "$\bar{b}$" generated by the program which will yield a velocity versus drag curve in the form $Y = \bar{a}x^{\bar{b}}$ for use in final data reduction.

B. ROLLING RESISTANCE SOFTWARE

As with the coastdown test software, software for the rolling resistance measurements is written in HP-41C/CV programming language and can be stored on magnetic cards or in calculator memory. The HP-41 calculator should be sized to 70 to allow the proper allocation of registers for data storage. Figure 15 is the flow diagram for the rolling resistance test sequence; a listing of the actual program steps with complete program description, sample data output, and storage registers utilized can be found in the Appendix.

C. INSTALLATION OF INSTRUMENTATION

The instrumentation used for the rolling resistance determination is the same as that used for coastdown testing with the addition of means for measuring the towing force. As shown in Figure 14, towing force is measured directly through the use of an instrumented tow bar attached to a towing adapter mounted on the vehicle. The strain gauges are wired to a bridge within the accelerometer/strain gauge interface unit and the bridge is powered by the same battery pack used in coastdown testing and hooked-up similarly. Channel 4 of the acquisition unit reads output voltage from the bridge. The instrumented tow bar has four pairs of strain gauges mounted as shown schematically in Figure 16. Strain gauge pairs one and three are designed to cancel

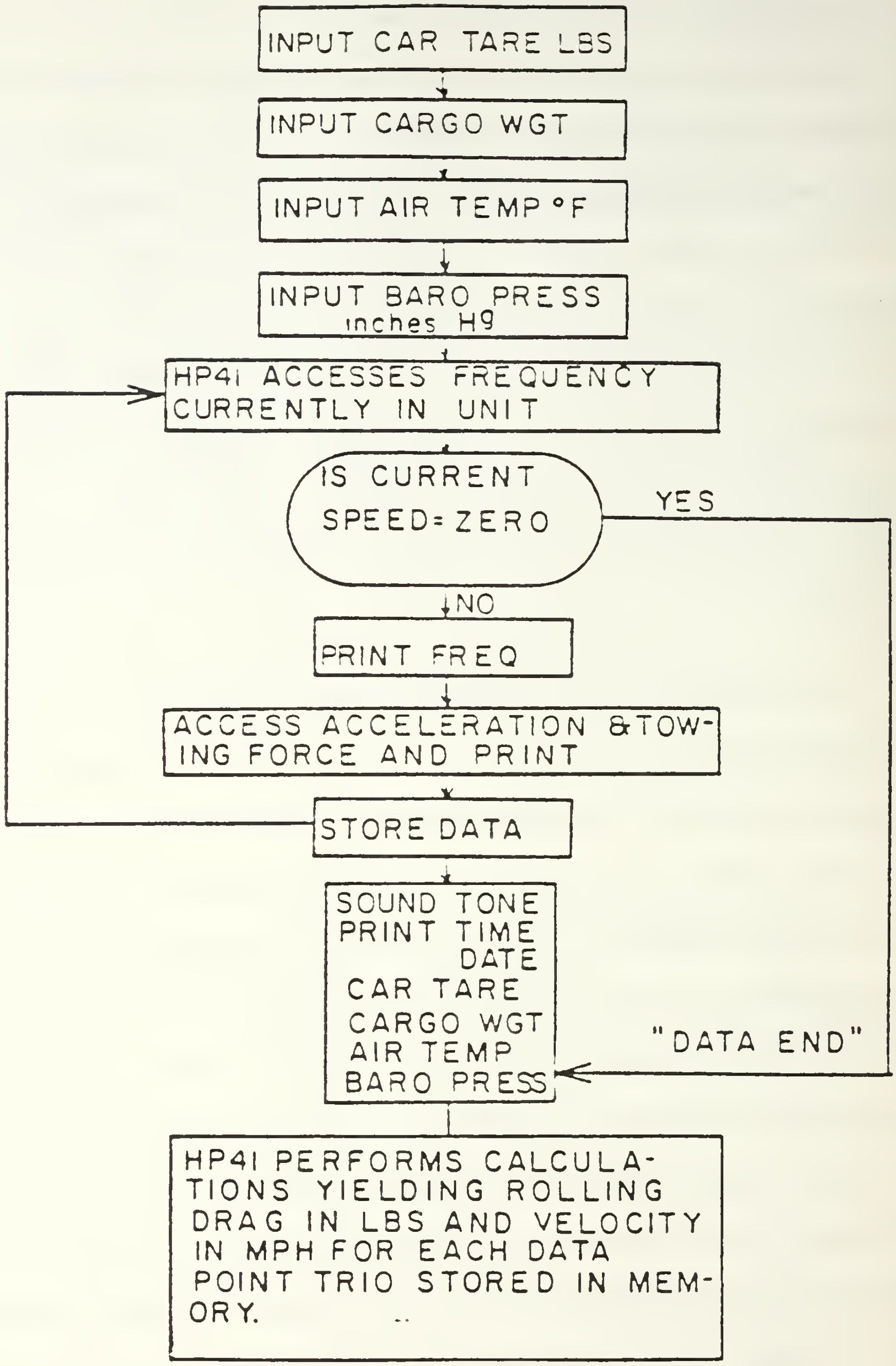

INPUT CAR TARE LBS
INPUT CARGO WGT
INPUT AIR TEMP °F
INPUT BARO PRESS inches Hg
HP41 ACCESSES FREQUENCY CURRENTLY IN UNIT
IS CURRENT SPEED=ZERO
YES
NO
PRINT FREQ
ACCESS ACCELERATION &TOWING FORCE AND PRINT
STORE DATA
SOUND TONE
PRINT TIME
DATE
CAR TARE
CARGO WGT
AIR TEMP
BARO PRESS
"DATA END"
HP41 PERFORMS CALCULATIONS YIELDING ROLLING DRAG IN LBS AND VELOCITY IN MPH FOR EACH DATA POINT TRIO STORED IN MEMORY.

Figure 15. Rolling Resistance Test Flow Diagram (Box)

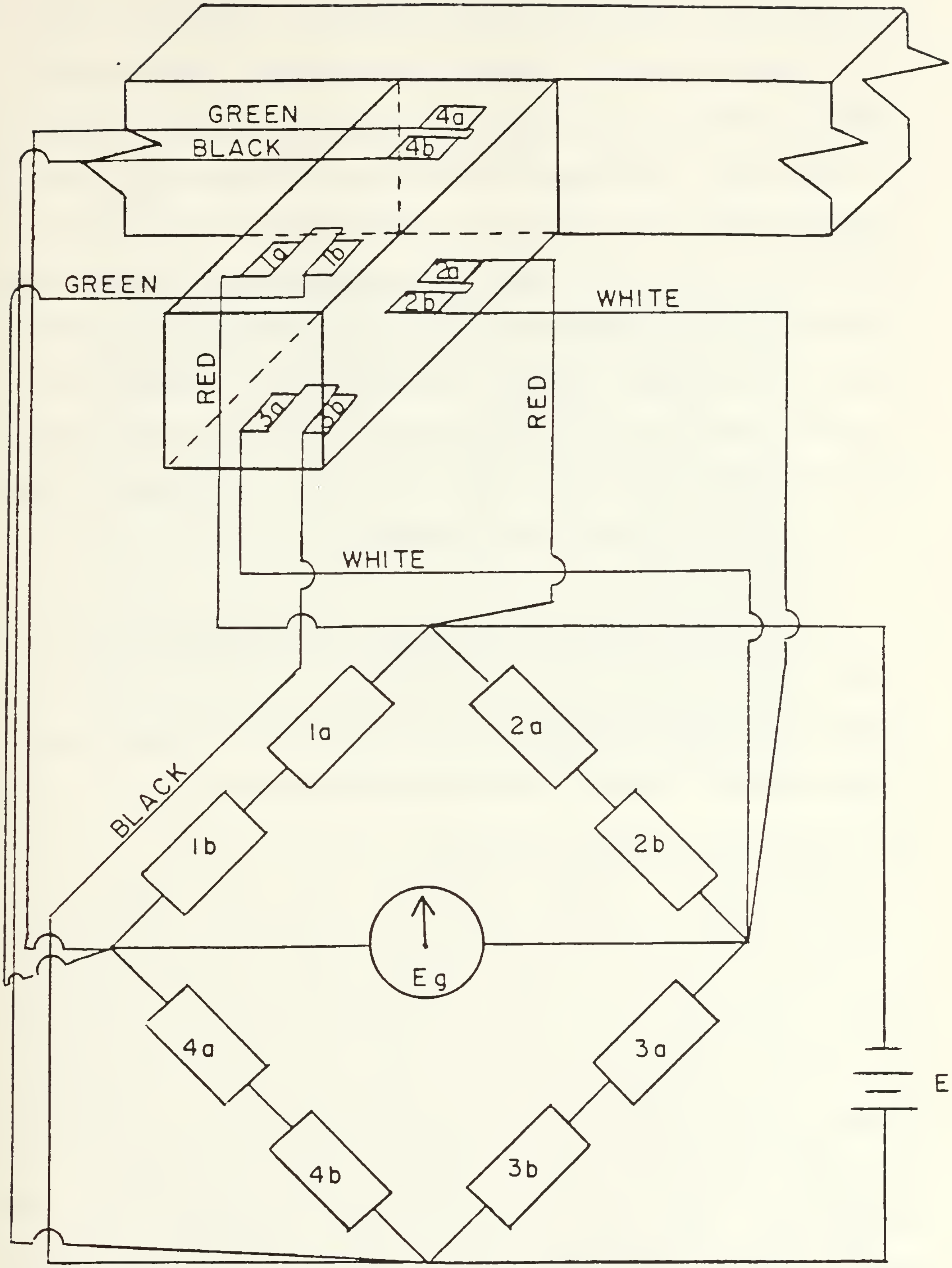


Figure 16. Schematic of Tow Bar Strain Gauge Installation

any bending in the horizontal direction. These two pair also provide Poisson ratio and temperature compensation. Details of the strain gauge characteristics can be found in the Appendix. Once power is applied to the bridge, using the ON/OFF-CHARGE switch on the accelerometer strain gauge interface unit, the potentiometer on the front of the interface unit may be used to zero the HP-41CV readout and balance the bridge. When a tensile force, produced by towing a vehicle, is applied to the instrumented tow bar, the resistances in the gauges change and the bridge output is driven by the following formula:

$$E_g = E\left[\left(\frac{1A + 1B}{1A + 1B + 4A + 4B}\right) - \left(\frac{2A + 2B}{2A + 2B + 3A + 3B}\right)\right]$$

Since the strain gauges are self-temperature-compensated, correction for apparent strain is unnecessary.

D. ROLLING RESISTANCE TRAILER

The shrouded rolling resistance trailer is equipped with a "doughnut" trailer coupler rather than the more conventional spherical ball cover and therefore must be attached to a towing vehicle equipped with a tow hook. The design height of the doughnut is eighteen inches and care should be taken to ensure that the height of the tow hook is compatible. Once the trailer has been attached to the towing vehicle and safety chains attached, the rear doors of the trailer may be opened and the test vehicle pushed inside until the front of the vehicle is within four or five feet of the instrumented tow bar. The adjustable tow bar is then attached to the bumper and frame of the test vehicle and the vehicle pushed in further until attachment of the adjustable tow bar to the instrumented tow bar can be accomplished. (Figure 17.) The instrumented tow bar can be adjusted for the height of the test vehicle bumper by inserting the attachment bolts at the proper level. Care should be taken to attach the tow bar's safety chains to the eye hooks on the front inside of the trailer.

Since the instrumentation for the rolling resistance test is the same as that employed for the coastdown test, installation of the instrumentation is essentially the same except that the cables from the apparatus in Figure 9 must now be attached to the interface panel on the trailer front (Figure 18) and the two data gathering devices attached to the interface panel from inside the trailer. After placing the apparatus in Figure 9 (except the accelerometer) in the front seat of the towing vehicle, follow the general procedure for interface loop hook-up in Section IV.C. of this manual. The two cables on the lower rear of the accelerometer/strain guage interface unit (ACCELEROMETER INPUT and TOW BAR INPUT) and the connector labelled OPTICAL SWITCH on the battery pack must be connected, by means of long jumper cables, to the similarly marked connectors on

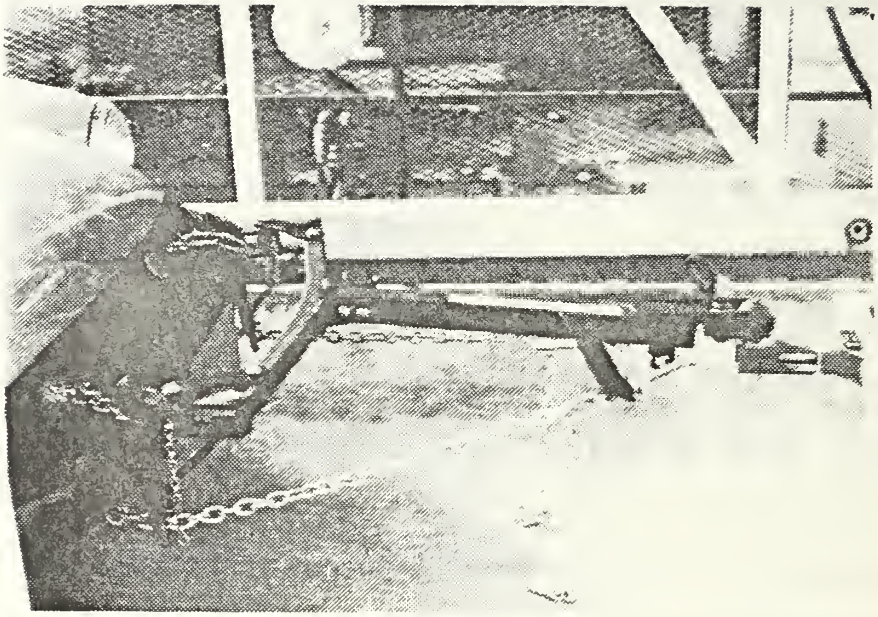


Figure 17. Tow Bar Attachments

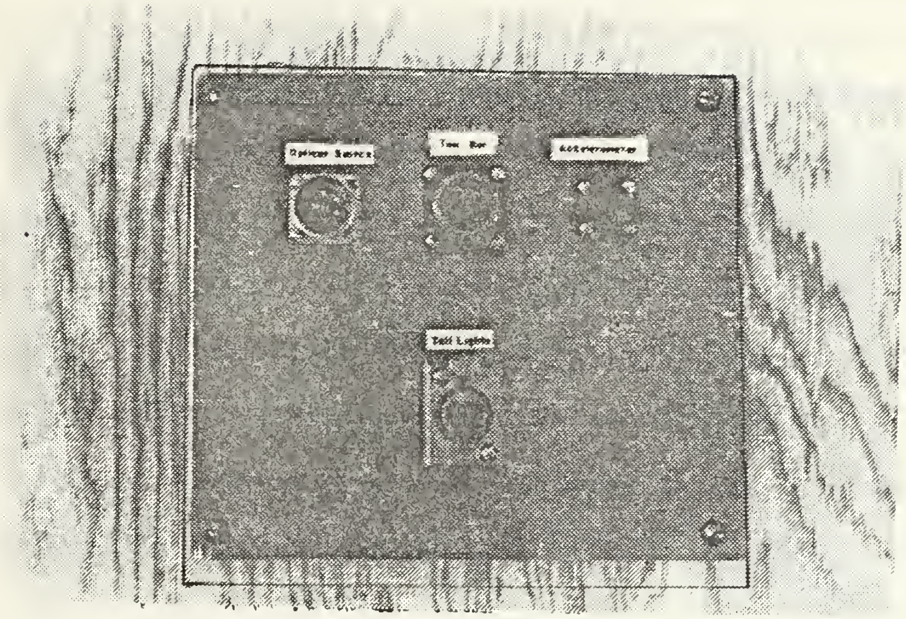


Figure 18. Interface Panel

the interface panel. The connector labelled tail lights is hard-wired to the combination running, stop, and turn signal lamps on the rear of the trailer. The wires from this connector must be attached to tail light wires on the towing vehicle.

The accelerometer may be placed on any convenient smooth surface in the test vehicle, preferably a window. The cable should be attached, by means of a jumper, to the appropriate connector on the rear of the interface panel. The fifth wheel should be fastened to the aluminum panel on the left side of the trailer (refer to Section IV.D. for instructions) and connected, by means of a jumper, to the appropriate jack on the rear of the interface panel. The instrumentation on the tow bar is hard-wired to the rear of the interface panel. Once these connections have been accomplished, the apparatus is ready for initialization and operation.

E. SYSTEM INITIALIZATION AND PROCEDURE

Begin by ensuring that the cigarette lighter connection is secure. With the calculator turned off, the channels 3, 4, and 5 wires disconnected, and the thermal printer turned on, depress the power switch on the front of the acquisition unit into the ON position. At this point, refer to Section IV.D. for notes on error indications and remote operation. If no error indications are seen in the lower right-hand corner of the liquid crystal panel, then all systems are functioning properly. Reconnect the channel 3, 4, and 5 wires on the rear of the acquisition unit. Place the ON/OFF CHARGE toggle switch on the interface unit in the ON (UP) position. Red numbers should appear on the LED readout. For accelerometer calibration, place the toggle switch labelled ACCEL/TOW in the ACCEL (UP) position. Calibration of the accelerometer is accomplished in the same manner as described in Section IV.D.

Next place the toggle switch labelled ACCEL/TOW in the TOW (DOWN) position. The LED and HP-41CV will now read output from the instrumented tow bar. The user will normally be in the Front Panel routine on the HP-41CV from previous calibration of the accelerometer. If this is the case, depress the "TAN" button on the calculator and the HP-41CV will respond with "XEQ J" and then "--------". (If the Front Panel routine was inadvertently exited, simply execute "FP" again; the system will reinitialize and "--------" will appear.) Depress the "A" button and the HP-41CV will respond with "DCV" followed by "channel?" Calibration of the tow bar on channel 4 is desired, so respond with "4" and then press "R/S". Channel 4 will close in the acquisition unit and then tow bar voltage readings will be continuously displaed on the HP-41CV. With a small jeweler's screwdriver, turn the tow bar "zero adjust" potentiometer on the face of the readout unit until a positive number is seen on the calculator, preferably less than 0.100. Remember this number as it will be inserted into the rolling resistance program for the tow tare (tow zero). The tow bar "full-scale adjust" is for sensitivity only and should not be used for zeroing. Finally, place the toggle switch labelled OPTICAL SWITCH on the battery pack in the ON (UP) position.

Rolling resistance testing is accomplished on the same long, straight, level segment of road that was used for the coastdown testing, preferably immediately after the coastdown test. This ensures that all the ambient information recorded prior to coastdown testing remains constant for the rolling resistance test. At this time review the information specified in Section IV.D. and ensure that it is still applicable. Unless the two tests are run concurrently under similar weather and road conditions, the results obtained may be meaningless. (Note: 58 pounds, the weight of the adjustable tow bar, should be added to the vehicle weight.)

Once the apparatus hook-up is complete, the instrumentation is ready for rolling resistance testing. The towing vehicle with trailer attached should be at the starting point of the test run prior to the following procedures. Activate the rolling resistance program within the HP-41CV by executing "BOX". The program will prompt the user for car weight, tow tare, cargo weight, air temperature, and barometric pressure. Input the prompted items, depressing the "R/S" button after each entry. DO NOT DEPRESS THE "R/S" BUTTON AFTER THE BAROMETRIC PRESSURE ENTRY. The program is now initialized and depression of the "R/S" button will activate the data search.

Unlike in coastdown testing, no maximum speed is necessary in rolling resistance testing and no coastdown needed. Prior to activating the program by final depression of the "R/S" button, begin a slow acceleration. This is necessary because once the data search is activated, the program will record speed, acceleration, and tow force ONLY for speeds greater than zero. Once a speed of zero is detected, the data search ends and data reduction begins. After program activation, accelerate to a speed convenient to the length of the test bed keeping safety and stopping distance in mind. No maximum speed is necessary; the program will access and record speed, acceleration, and tow force in groups of three repeatedly until a speed of zero is detected. The user should plan ahead and allow a distance for deceleration to a smooth stop. The idea is to obtain as many data points as possible in a wide speed range over the allotted testing distance; this will result in a smooth curve fit.

Once a speed of zero is detected, the program will halt data acquisition and begin data reduction. The calculator will perform computations and print out a list of measured velocities in miles per hour and drag in pounds for each trio of data points obtained during the rolling resistance test. (See samples in Appendix.)

Using the rolling drag as Y values and the velocity as the X values, enter the "POW" subroutine of the HP-41CV "LIN" program and calculate the constants "$\bar{a}$" and "$\bar{b}$" which the "POW" program computes. These constants correspond to a curve of velocity versus drag in the form $Y = \bar{a}x^{\bar{b}}$. Record these constants, as they will be needed in the final data reduction program to determine aerodynamic drag coefficients.

VI. DETERMINATION OF AERODYNAMIC DRAG COEFFICIENT

Final data reduction results in the determination of the aerodynamic drag coefficient, Cd, and is accomplished with the third program entitled "AERO". At this point, coastdown testing and rolling resistance testing have been completed and the constants "a", "$\bar{a}$", "b", and "$\bar{b}$" have been obtained from the POW program, based on the data obtained during testing. Only the HP-41CV calculator is required for final data reduction. The following input data are required:

a. density lbm/ft^3
b. viscosity lbf-sec/ft^2
c. vehicle frontal area ft^2
d. constants "a" and "b" from CDT
e. constants "$\bar{a}$" and "$\bar{b}$" from BOX

The flow diagram for AERO is shown in Figure 19. The program, upon execution, prompts the user for the above information and then calculates values for aerodynamic drag, velocity, drag coefficient, and Reynold's number for speeds beginning at 65 miles per hour and ending at 0 miles per hour using 5 miles per hour intervals. A sample output is included in the Appendix. A listing of actual program steps with complete program description and list of storage registers utilzed can also be found in the Appendix.

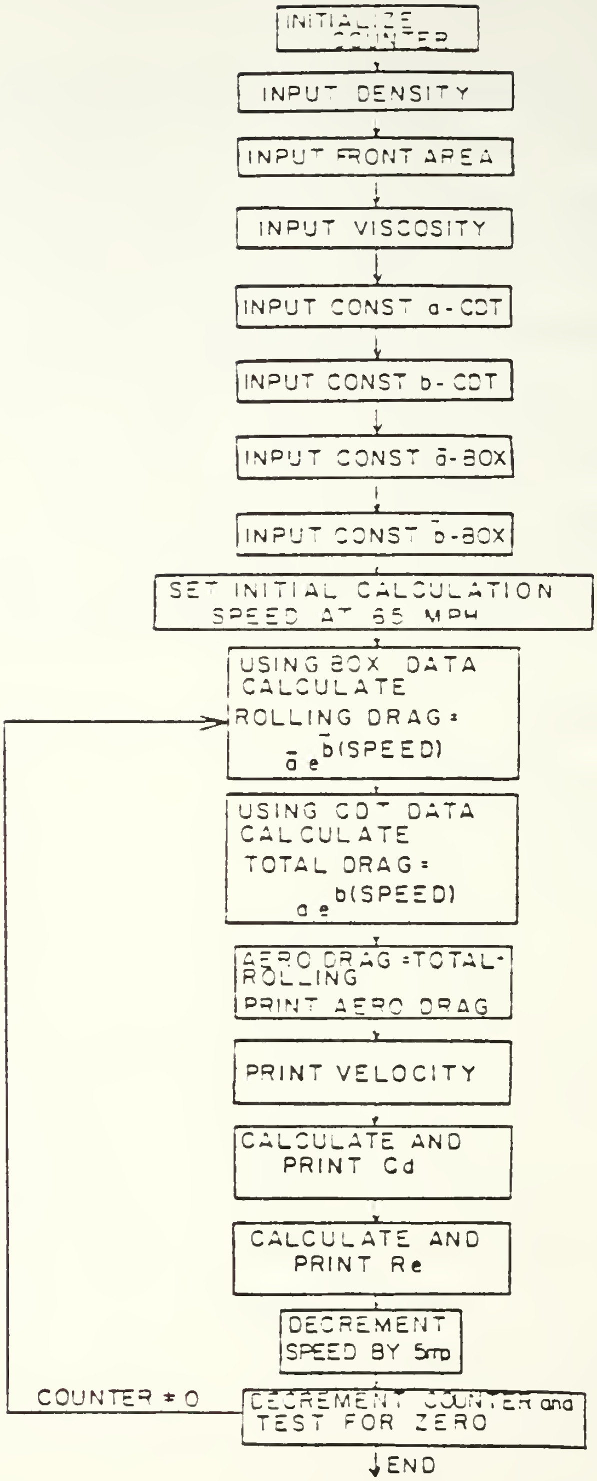


Figure 19. Final Data Reduction Flow Diagram

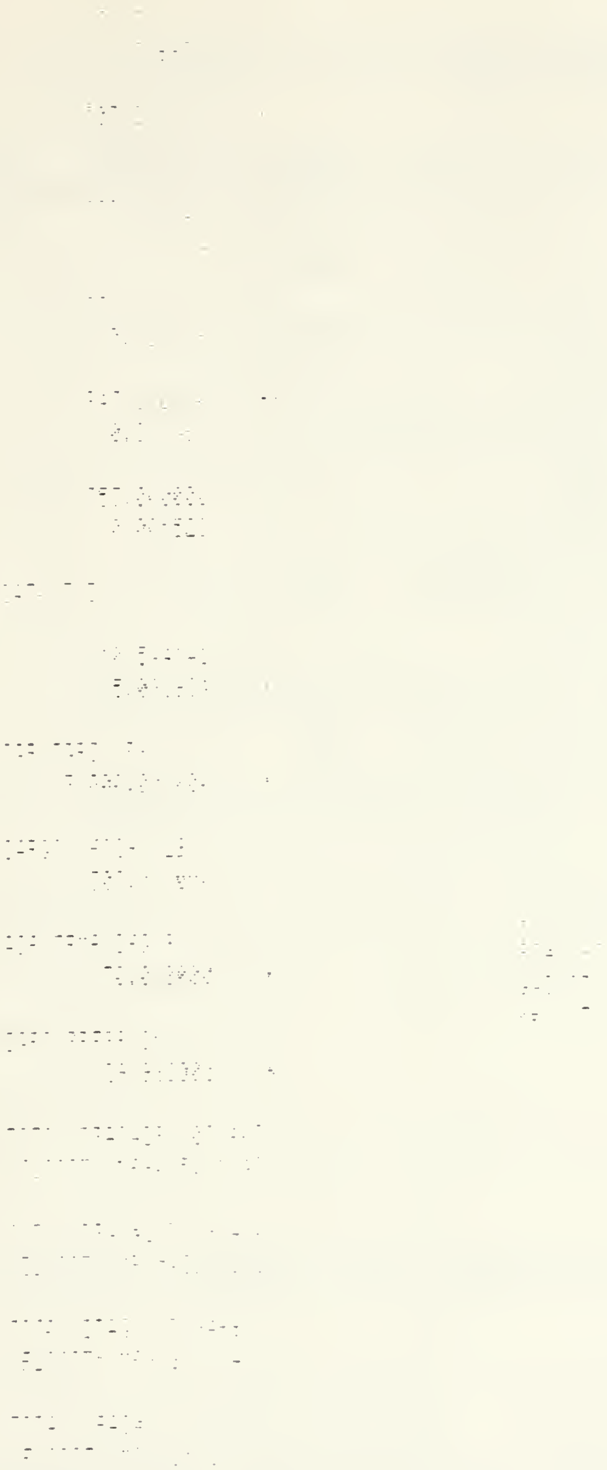
PROGRAM EXECUTION

With the "AERO" program stored in calculator memory, execute "AERO" on the HP-41. The program will prompt the user for density, viscosity, frontal area, and the constants from the individual tests. Frontal area may be measured from a frontal photograph of the vehicle taken with a long enough focal length lens to allow the camera to be at least ten car lengths from the vehicle. A planimeter should be used to determine actual frontal area using a reference area included in the photograph. Upon depression of "R/S" after the final entry, the program will make all calculations and produce a complete printout of the results.

APPENDIX

[illegible]

Coastdown Program Listing



Sample Coastdown Data Output
(simulated data)

COASTDOWN TEST SOFTWARE (CDT)

The following is a list of the storage registers utilized:

00 counter

01 car tare (lbs)

02 cargo weight (lbs)

03 (total weight) * (32.2 ft/sec^2)

04 air temperature (°F)

05 barometric pressure (inHg)

06 reference speed in Hz

07 indirect storage (registers 26,28,30,...54)

08 indirect storage (27,29,31,...55)

09 indirect storage (registers 10,11,12,...25)

10 total drag (lbs)
↓ ↓
25

26 frequency

27 voltage
↓ ↓
55

A description of the coastdown test program, step-by-step follows:

01 labels program as CDT

02 SF 21 printer enable flag-enables HP-41CV/printer interface

03 CLRG clears all storage registers

04 FIX 5 sets number of significant digits after decimal to be displayed

05,06 stores #26 in storage register 07

07,08 stores #27 in storage register 08

09,10 stores #10 in storage register 09

At the initial speed of 60 miles per hour, the corresponding frequency and voltage are stored in registers 26 and 27, respectively. The total drag calculation is stored in register 10. At each speed decrement, the numerical value of each of the storage registers will be increased by one, and the corresponding frequency, voltage, and total drag stored appropriately. Hewlett-Packard calls this indirect storage.

11,12 the number 15 is stored in register 00; this will be the maximum number of data points able to be stored and operated on.

13-15 upon program execution, prompts user for decrement, i.e., 5 miles per hour or 10 miles per hour

16-37 If a 5 was entered on the previous prompt, the value 252.1024 is stored in register 56; if a 10 was entered, the value 504.2048 is stored in register 56; if any other entry is made, the program ignores it and re-prompts user for desired decrement.

38-41 prompts user for car tare in pounds and stores in register 01

42-44 prompts user for cargo weight in pounds and stores in register 02

45-49 adds car tare to cargo weight and stores in register 03

50-52 prompts user for air temperature in degrees fahrenheit and stores in register 04

53-55 prompts user for barometric pressure in inches mercury and stores in register 05

56,57 stores the frequency equivalent of 60 mph in register 06, i.e., 3025.2288 Hz

58 internal label statement

59,60 recalls search frequency from storage and tests to determine zero equivalency. If search frequency equals zero, then all data points have been obtained and the HP-41CV proceeds with data reduction; if search speed does not equal zero, the program continues

61 if the search speed equals zero, the program is commanded to go to internal label 03 and proceed from there

62 if the search speed does not equal zero, the program proceeds from this step; the frequency (speed) in register 06 is entered into the Y-register of the HP-41CV

63 internal label for looping purposes

64-66 HP-41CV accesses channel 3 of the data acquisition unit and places the current frequency in the X-register of the HP-41CV

67 determines whether the accessed frequency is less than or equal to the desired frequency

68 directs program to LBL 01 if accessed frequency is less than or equal to the desired frequency

69,70 places current speed increment in Hz back into Y-register

71 directs program to LBL 05 to renew search for designated speed

72-74 sounds tone and prints frequency

75 indirect storage of frequency into register indicated by register 07

76-80 HP-41 accesses current acceleration information and prints it

81 indirect storage of acceleration into register indicated by register 08

82,83 decrements speed by frequency input in steps 16-37

84,86 increments storage register indirectly

87 directs program to LBL 02 to begin search for next speed decrement

88-91 prints DATA END

92,93 prints current time (HRS.MIN)

94-96 prints current date (MONTH,DAY,YEAR)

97-100 stores #26 and #27 in storage registers 07 and 08, respectively

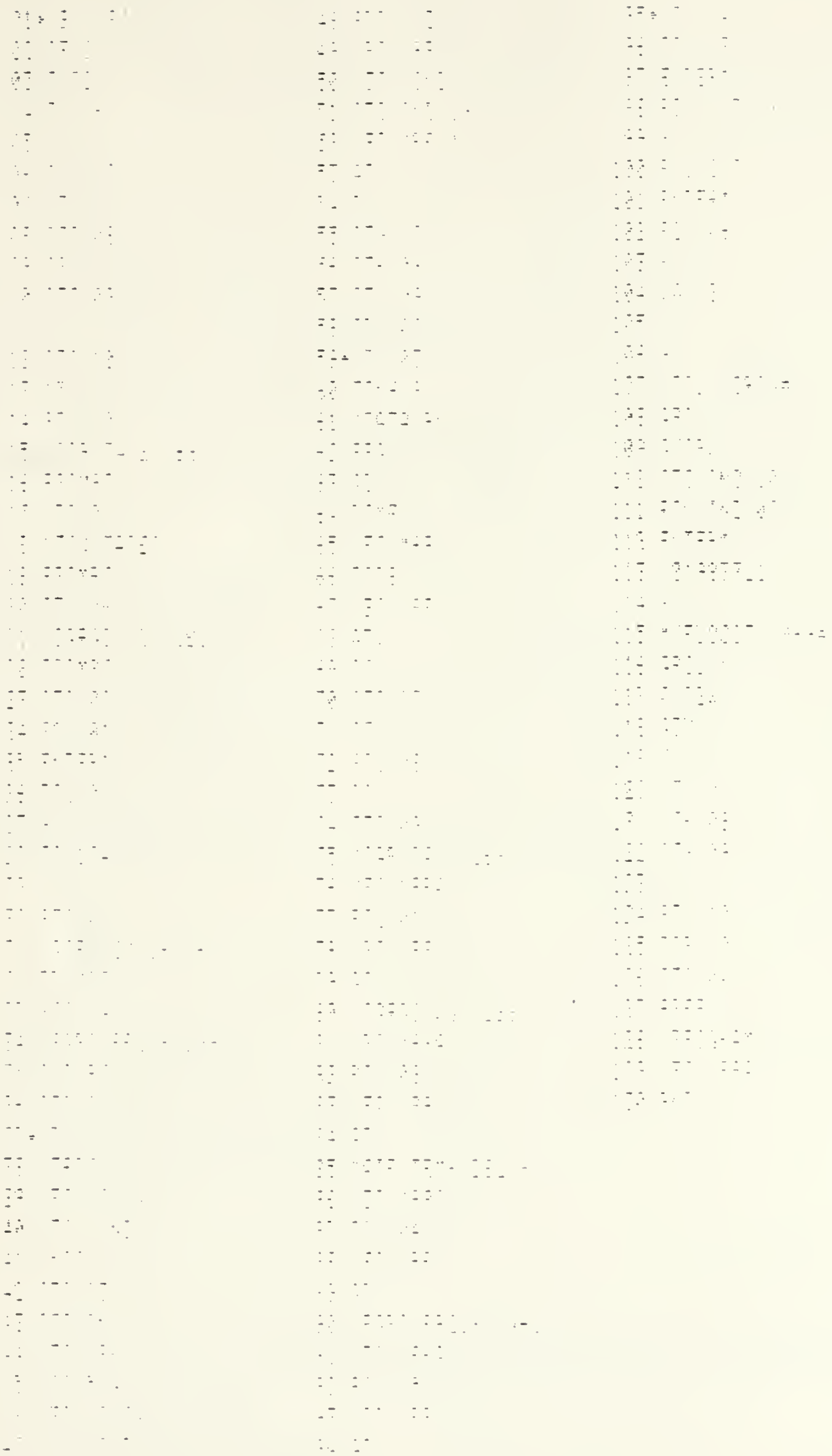
100-120 prints all data input in steps 16,19,27, and 30

121 internal label

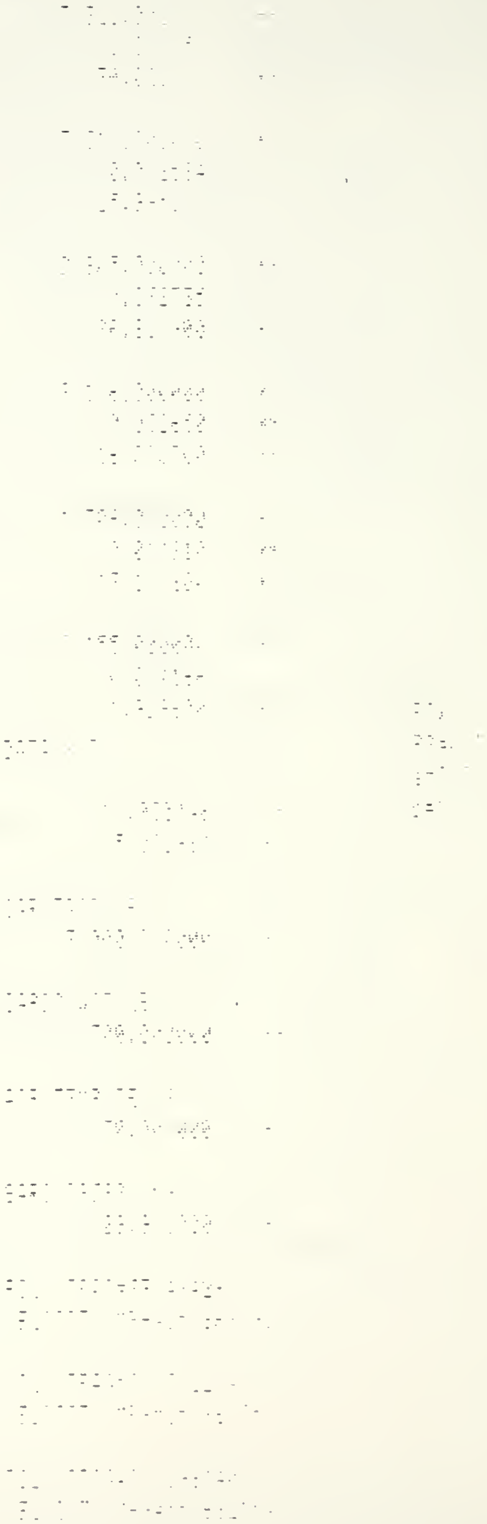
122-148 recalls from memory, in pairs, the voltage corresponding to the speed, converts them to total drag and miles per hour, respectively, and prints them. The program will do the calculations for a maximum of 15 pairs. Zeroes will be printed when the information from memory is exhausted

One then executes the POW program found in the LIN curve-fit program from the Math PAC module. Using the CDT printout as reference, input the values of total drag and velocity for Y and X, respectively. Continue doing this until all drag-velocity pairs have been entered. The POW program will yield numerical values for two constants called a and b. These constants appear in the curve-fit formula for total drag versus speed:

$$Y\text{ (drag, pounds)} = a\,X\text{ (speed, miles per hour)}^{b}$$



Rolling Resistance Program Listing



Typical Rolling Resistance Data Output
(simulated data)

ROLLING RESISTANCE TEST SOFTWARE (BOX)

The following is a list of the storage registers utilized:

00	counter
01	car tare (lbs)
02	cargo weight (lbs)
03	(total lbs) * (32.2 ft/sec^2)
04	air temperature (°F)
05	barometric pressure (inches Hg)
06	tow tare
07	indirect storage
08	indirect storage
09	indirect storage
10	indirect storage
11	rolling drag lbs
↓	↓
25	
26	frequency (speed)
27	voltage (acceleration)
28	voltage (towing force)
↓	↓
70	

A description of the rolling resistance test program, step-by-step, follows:

01 labels program as BOX

02 SF 21 printer enable flag-enables HP-41CV/printer interface

03 ClRG clears all storage registers

04 FIX 6 sets number of significant digits after decimal to be displayed

05,06 stores #26 in storage register 07

07,08 stores #27 in storage register 08

09,10 stores #28 in storage register 09

11,12 stores #11 in storage register 10

13,14 stores #15 in storage register 00 to be used as counter decrement

15-17 prompts user for car tare in pounds and stores register 01

18-20 prompts user for tow tare and stores in register 02

21-23 prompts user for cargo weight and stores in register 02

24-30 adds cargo weight to car tare, divides this sum by 32.174 and stores result in register 03

31-33 prompts user air temperature in ^{o}F and stores in register 04

34-36 prompts user for barometric pressure in inches Hg and stores in register 05

Now, all the preliminary data has been entered and stored. There is no initial speed search as in coastdown testing. The program will acquire and record a frequency and two corresponding voltages and store them in registers 26, 27, and 28, respectively. The total rolling drag calculation is stored in register 10. After each data trio is acquired and stored, the numerical value of the four storage registers will be increased by one, and successive readings stored in a similar manner. The HP-IL system continues to acquire readings until a frequency of zero is sensed.

37 internal label used as reference

38-40 HP-41 accesses channel 3 of the acquisition unit and places the current frequency in its X-register

41 determine whether accessed speed is equal to zero

42 if accessed speed is equal to zero, program is directed to end data search and begin data reduction

43,44 if accessed speed is not equal to zero, it is stored indirectly in storage register indicated by register 07 and printed

45-53 HP-41CV accesses channels 5 and 4, picks off the voltages present, prints them, and stores them indirectly in the storage registers indicated by registers 08 and 09, respectively.

54-57	increments, by 3, the storage registers indirectly indicated by registers 07, 08, and 09
58	HP-41 again accesses frequency and begins printing and storage of another data trio
59	internal label statement-program is directed here when a frequency of zero is sensed
60-63	tone is sounded indicating end of data acquisition and DATA END is printed
64-68	current date and time are printed
69-74	storage registers 07, 08, and 09 are again stored with the numbers 26, 27, and 28, respectively
75-94	all inputs at beginning of program are recalled from memory and printed
95	internal reference label-indicates beginning of data reduction subroutine
96,97	recalls (W/g) and stores in Y-register
98,99	recalls acceleration data from indirect storage in register 08 and multiplies it by (W/g)
100-106	recalls drag force data from indirect storage in register 09, (subtracts tow tare, divides by pound/volt calibration constant) and adds it to the total in step 95,96
107-110	prints rolling drag and stores in register indirectly indicated by register 10

111,112	recalls frequency data indirectly stored in register indicated by 07 and places it in the Y-register
113,114	multiplies the frequency by the proper conversion factor to yield miles per hour
115-118	prints velocity in miles per hour
119-122	increments the storage register indirectly stored in registers 07, 08, and 09 by three
123,124	increments the storage register indirectly stored in register 10 by one
125	decrements number of iterations by one
126	returns to label 04 to begin data reduction on the next trio of stored data points
127-130	when 15 sets of data have been reduced, the program "beeps" signalling end of data reduction and prints PROGRAM END

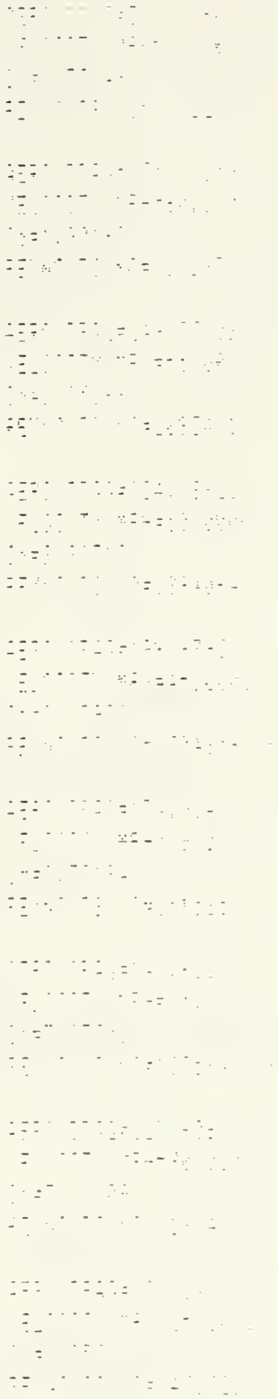
One then executes the POW program found in the LIN curve-fit program from the Math PAC module. Using the BOX printout as data (Figure 16), the values of rolling drag and velocity are input for the values of Y and X, respectively. Once all the drag-velocity terms have been entered, the POW program will yield numerical values of two constants, $\bar{a}$ and $\bar{b}$ which appear in the following curve-fit formula:

$$Y = \bar{a}X^{\bar{b}}$$

These constants will be used in final data reduction.

[illegible]

Data Reduction Program Listing



Typical Data Reduction Program Output
(simulated data)

DRAG COEFFICIENT DETERMINATION

The following is a list of storage registers utilized:

00 counter

01 density (lbm/ft^3)

02 frontal area (ft^2)

03 viscosity (lbf-sect/ft^2)

04 CDT constant a

05 CDT constant b

06 BOX constant $\bar{a}$

07 BOX constant $\bar{b}$

08 starting speed

09 total drag based on given speed

10 aerodynamic drag based on subtraction of rolling drag from total drag

11 speed (ft/sec)

12 frontal area (ft^2)

A description of the aerodynamic drag coefficient program, step-by-step, follows:

01 internal label AERO

02 enables printer

03 clears all storage registers

04 instructs calculator to start at 14 and decrement by one after each iteration

05 stores counter in register 00

06-08 prompts for density in lbm/ft^3 and stores in register 01

09-13 prompts for frontal area in ft^2, takes square root, and stores in register 02

14-19 prompts for viscosity in lbf-sec/ft^2, multiplies by 32,174, and stores in register 03

20-22 prompts for CDT constant a and stores in register 04

23-25 prompts for CDT constant b and stores in register 05

26-28 prompts for BOX constant $\bar{a}$ and stores in register 06

29-31 prompts for BOX constant $\bar{b}$ and stores in register 07

32,33 stores initial speed of 65 miles per hour in register 08

34 internal label reference

35-45 calculates rolling drag using the formula below and stores in register 09:

$$\text{Rolling Drag} = \bar{a}\,(\text{mph})^{\bar{b}}$$

46-45 calculates total drag using the formula below, subtracts rolling drag, and stores result in register 10

$$\text{Total Drag} = a\,(\text{mph})^{b}$$

55-57 prints AERO DRAG

58-61 prints VELOCITY MPH

62-75 calculates aerodynamic drag coefficient using the following formula:

$$\mathrm{Cd} = \frac{(\mathrm{AERO\ DRAG})(32.2)}{(.5)(\mathrm{density})(\mathrm{mph} * 1.47)^2(\mathrm{FRONTAL\ AREA})}$$

76-78 prints Cd

79-86 calculates Reynold's number using the following formula:

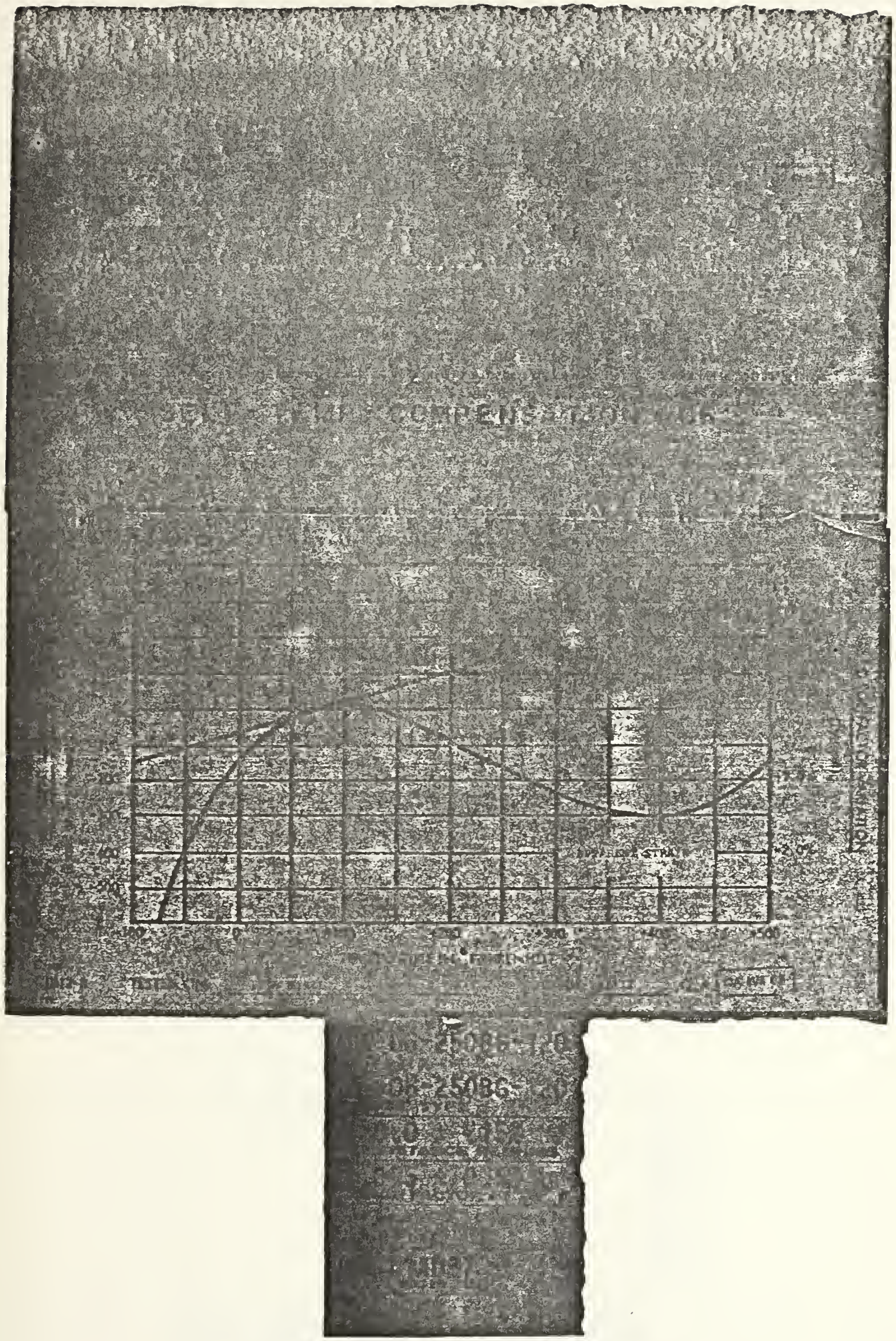
$$\mathrm{Re} = \frac{(\mathrm{density})(\mathrm{mph} * 1.47)(\mathrm{FRONTAL\ AREA})}{(\mathrm{VISCOSITY})}$$

87-90 prints Re

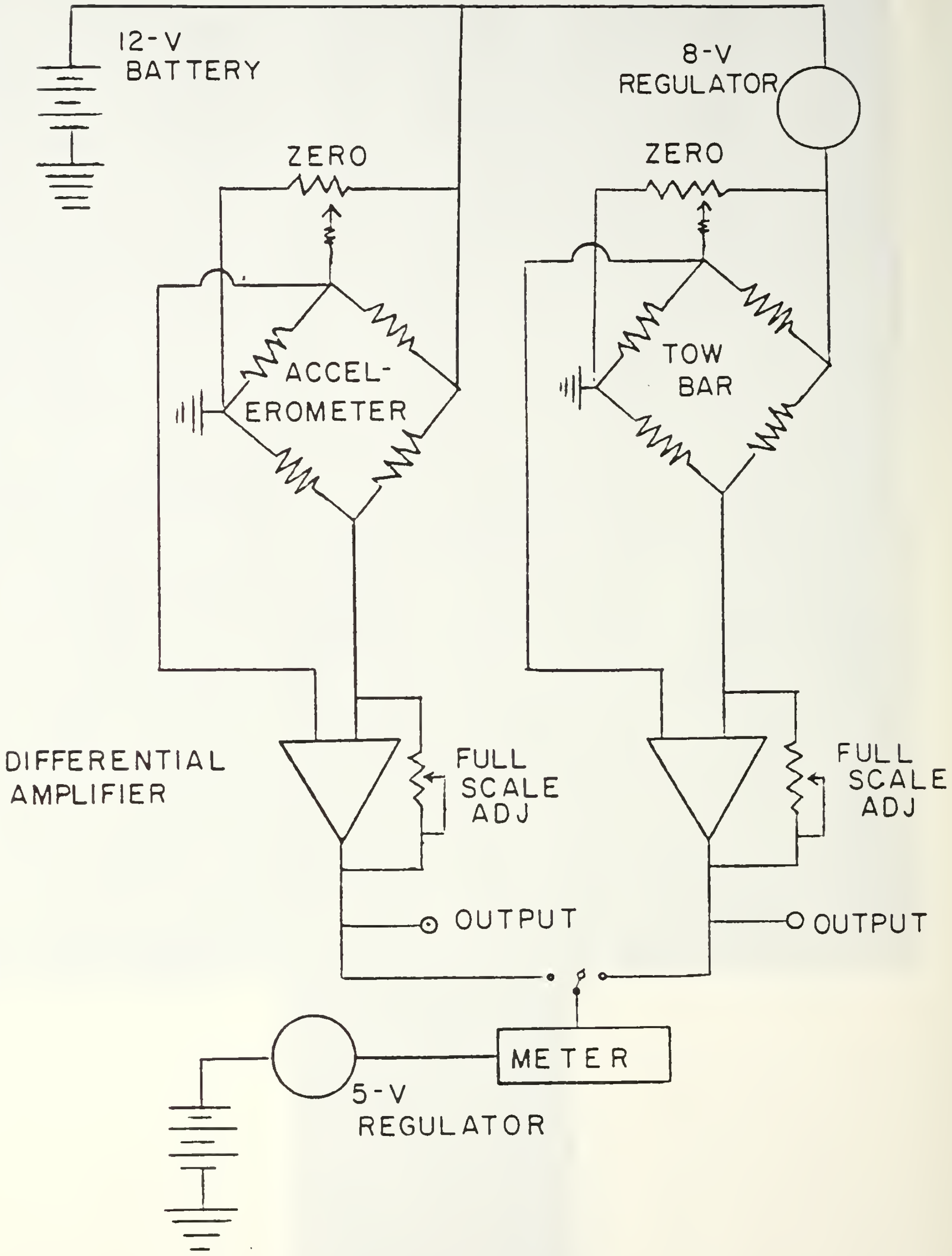
91,92 decrements speed by 5 miles per hour

93,94 checks for counter equal to zero; if not equal to zero, decrement counter by one and return to label 01 for another set of calculations using another speed

95-98 end sound tone and print PROGRAM END



Strain Gauge Information



Schematic of Interference Unit

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